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Plant genetic resources

A review of current research and future needs

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Foreword

After several promising years, hunger and malnutrition are again on the rise. The latest edition of '*The State of Food Security and Nutrition in the World*', published jointly by five UN agencies[1], estimated that in 2019 almost 690 million people went hungry, an increase of nearly 60 million over the previous five years. This occurred against a complex and alarming backdrop of growing economic, racial, and social inequality, persistent and widespread environmental degradation, continually expanding human populations, rapidly changing climates and a weakening of the architecture of international cooperation. Most recently, the global disruption caused by COVID-19 has further exacerbated the situation.

Within this web of inter-connected challenges, biodiversity continues to be lost at an alarming rate in spite of the best efforts of many individuals, organizations and nations. A report published by the Convention on Biological Diversity in September 2020, '*Global Biodiversity Outlook 5*', concluded that none of the 20 Aichi biodiversity targets agreed to by the parties to the Convention in 2010 had been fully achieved, and only six had been partially achieved. The failure to adequately stem the loss of biodiversity has significant implications not only for the environment but also for human wellbeing, even survival.

A critically important component of biodiversity is that which feeds and clothes us, in particular the genetic diversity within and among our domesticated animals, cultivated crops and their wild relatives. This vast diversity underpins agriculture, and its deployment helps us to meet the challenges and opportunities of today's world and as well as the unknown circumstances that will prevail tomorrow.

In 2019, the Food and Agriculture Organization of the United Nations (FAO), published 'T*he State of the World's Biodiversity for Food and Agriculture*'. The report pointed out that as in the case of biodiversity in general, many components of agricultural biodiversity remain under threat. For crops, neglected and underused species in particular remain under-represented in *ex situ* collections and in many parts of the world the use of landraces and traditional farmer varieties continues to decline in local farming systems. However, the situation is highly complex, and the news is not all bad, especially for those crops for which past conservation efforts are paying off handsomely. Although a great deal remains to be done, many countries are expanding the range of genetic resources that they conserve *ex situ a*nd many farmers who have adopted modern varieties also continue to maintain traditional landraces.

1 FAO, IFAD, UNICEF, WFP and WHO

But there is no room for complacency and the situation for crop wild relatives is even more concerning. This is particularly so in regions experiencing severe climate change and widespread degradation of habitats, and where species migration is limited by ecogeographical and other barriers.

Why should we be concerned? For the simple reason that agricultural genetic diversity represents a very powerful tool in our efforts to meet a wide variety of current and future challenges. The genetic resources of our crops underpin our ability to breed new cultivars that can help make agriculture more sustainable and productive within a rapidly changing world. Such cultivars could, for example, provide more nutritious food, novel products, be more resilient to pests, disease and environmental stresses, or have the ability to sequester more carbon.

Thus, crop genetic diversity provides a basis for making significant inroads into improving the lives and wellbeing of humanity as well as the environment in which we all live. However, in order to play this role effectively, genetic diversity must be safely conserved and wisely used, and in both of these areas we can do better. Although we know much about how best to safeguard and use genetic resources there are still major areas where further research is needed. This book makes a very important contribution to this effort through providing an up-to-date overview of the current state of scientific research and provides some invaluable pointers to future research needs and opportunities.

This book does not go into detail about the current state of scientific plant breeding as this is a topic that has been well covered in other recent publications. What if provides is an extensive, much-needed and detailed coverage of a broad range of topics, from the importance and value of plant genetic resources and key methods for conserving them, through to their international exchange and local dissemination through more effective seed systems.

The senior editor of the book, Ehsan Dulloo, is to be congratulated on such a timely and useful publication. Furthermore, the range of authors of the individual chapters and the institutions they represent is truly impressive and reads like a Who's Who of plant genetic resources!

At the time of writing, the parties to the Convention on Biological Diversity are working to finalize a '*post 2020 global biodiversity framework*' to supersede the Aichi targets. The framework aims to act as a steppingstone on the way to achieving the Convention's 2050 Vision: '*By 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people.*' The current version of the framework envisages several long-term goals for biodiversity in general, including maintaining genetic diversity, and the fair and equitable sharing of benefits arising from its use. It is greatly to be hoped that in the final, agreed text this will be further built upon to ensure that the importance of genetic resources for food and agriculture, and their potential contribution to achieving the Sustainable Development Goals are fully recognized.

I commend this book to all who share these aims.

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Introduction

Plant genetic diversity is fundamental for ensuring global food and nutrition security. Its importance cannot be underestimated as it provides the genetic materials for humankind to continue produce food sustainably in the face of global challenges such as pest and diseases, land degradation, climate change and other socio-economic changes that are occurring today and that will take place in future. While at the global level, their importance is widely recognised as evidenced by the Convention on Biological Diversity and the International Treaty on Plant Genetic Resources for Food and Agriculture, and political processes established for monitoring the conservation and use of genetic resources, we find at the national and local levels that the conservation and use of plant genetic diversity are not getting the attention they deserve with the result that much of the diversity are eroding away, thereby undermining agriculture as a whole. Some key challenges include a narrowing genetic base for many key crops, the loss of landraces and wild relatives, due to agricultural intensification and urbanisation, land and soil degradation, the lack of support to minor and under-utilized crops that are locally and regional important. There is a need to develop the role of existing gene banks from repository of genetic diversity to enablers of the flow of germplasm and genetic information for breeding more robust varieties. There is equally an urgent need to stop the erosion of genetic diversity from their sites where they have developed their distinctive characteristics (in situ) such that the diversity among them can continue to evolve and develop traits for future use.

This volume examines the wealth of research addressing these challenges and the opportunity for a more integrated, global approach to protecting and leveraging plant genetic diversity for a more sustainable agriculture. Part 1 assesses the importance of valuing conservation and the use plant genetic diversity. Part 2 discusses protecting plant genetic diversity with *in-situ* and on-farm strategies. The final section reviews ways of enhancing conservation and the use of plant genetic diversity, including community-based conservation of crop genetic resources, participatory plant breeding programmes and more effective seed systems.

Part 1 Importance and value of conservation and use of plant genetic diversity

Part 1 of the book begins with a discussion of plant genetic resources for food and agriculture for sustainable development. Chapter 1 reviews relevant international agreements, instruments and mechanisms, which address the conservation, sustainable use and access and benefit-sharing for these resources along with their remarkable contributions to food security and nutrition. The chapter also highlights the state-of-the-art for the scientific and technological methods used to conserve and add value through genetic gains to these resources. Underscoring the importance of collaborations at various scales, the authors call for continued global coordination and partnerships on the internationally agreed activities for conserving effectively and deriving the most benefits sustainably from these irreplaceable resources.

Chapter 2 examines valuing past, present and future plant genetic resources in genebanks. The chapter summarises the main messages from applied economics literature on genebank values that began in the late 1990s, a recent set of studies undertaken by the CGIAR Genebank Platform and Crop Diversity Trust, and assessments of national genebanks. Three points are salient: the value of information; the demand for a diversity of approaches to document the diversity of ways that genebanks benefit society; and the need to establish priorities for collecting and conservation based on cost-effectiveness. Cost-effectiveness will require a) carefully targeted investments in characterization, evaluation, and genotyping, along with management of the resulting data, and its use to develop packages of breeder- and researcher-oriented materials, and b) investment in supportive research and various organizational optimization procedures, including automation.

The subject of Chapter 3 is monitoring plant genetic resources for food and agriculture. The chapter reviews the methodologies developed to assess the extent of diversity of PGRFA at species, variety, and genetic level and examines the efforts made at global level in monitoring them at different scales. Efforts have been made to halt the loss of biodiversity (including genetic diversity) by United Nations Organizations (FAO, UNEP, UN) at setting of global targets (second Global Plan of Action on conservation and sustainable use of PGRFA, Aichi Targets and Sustainable Development Goals) and indicators have been established to monitor progress towards them. Yet none of the targets on genetic diversity have been achieved, due to a lack of implementable monitoring system that would allow progress to be accurately monitored. Further research is needed to improve the methodologies for monitoring plant genetic resources, particularly at the varietal and genetic level. The chapter discusses the opportunities and challenges as well as provides recommendations for future conservation and monitoring strategies that may safeguard PGRFA for posterity.

The final chapter of Part 1 reviews improving the global exchange of germplasm for crop breeding. Different norms, rules and practices organize the exchange of germplasm to address broader global challenges such as advancement of science and innovation, food security, sustainable agriculture or global equity. Some of these institutions are now embedded in various treaties and national regulations. Chapter 4 claims that these regulations are not as successful as they could be because they fail to effectively integrate the complexity of the exchange environment. In order to better understand how exchange could be improved, it is important to go beyond a legalistic approach to exchange and look at the broader socio-technical context in which these exchanges take place. By developing an analytical framework that includes several dimensions beyond the regulatory one, this contribution creates the foundation for a more comprehensive approach that acts upon the relationship between germplasm and the diversity of institutional logics, germplasm and its resource system, and germplasm and its social environment.

Part 2 Protecting plant genetic diversity: in-situ and on-farm strategies

The first chapter of Part 2 assesses key steps in conservation and use of plant genetic resources: an overview. Chapter 5 begins by providing an example of a model which includes a series of steps starting with the full range of genetic diversity for all the target plant taxa, through the prioritisation of target taxa, the planning and the implementation of conservation action, leading through characterisation and evaluation, and utilisation in the development of novel crop varieties by farmers and/or breeders. The chapter then goes on to discuss conservation planning which is then followed by a review of the different strategies and techniques that are used in conservation. A section on the link between conservation and utilization is also included, before providing a conclusion that emphasises the importance of maintaining the current wealth of natural plant diversity.

Chapter 6 addresses key issues facing genebanks in preserving crop genetic diversity ex situ: an overview of the range of challenges. Local crop genetic diversity is challenged with changes in land use, urbanization, land degradation, changes in agricultural practises, availability of improved varieties, changes in market preference, and the impact of climate change. Efforts have been made to secure plant genetic resources ex situ for future use but there are significant issues related to cost effective, efficient, secure, rational, and sustainable long-term ex situ conservation. The chapter begins by addressing issues for the composition of ex situ collections and moves on to discuss issues for routine operations for conservation. It also highlights issues for the use of conserved genetic resources, before concluding with a summary of why the development of sustainable genebank systems is so important.

The next chapter examines the techniques and key issues in collecting Crop Wild Relatives (CWR). The genetic diversity found in populations of crop wild relatives is an essential resource for future crop breeding, but populations are at risk of loss before germplasm has been fully conserved in genebanks. Chapter 7 describes best practice for targeting and identifying species, and review knowledge about the variation in wild plant populations to guide the timing of collecting and approaches for genetic sampling. Indicators are presented for seed quality, ripeness and dispersal. Techniques for collection of seed, herbarium vouchers and associated data are reviewed with examples drawn from the Adapting Agriculture to Climate Change (Crop Wild Relative) project. Further research is needed to find optimal approaches for handling of seed to ensure high longevity of seed collections, and improved tools are needed to guide sampling of genetic diversity of crop wild relatives.

Moving on to Chapter 8, this chapter discusses new technologies to improve the *ex-situ* conservation of plant genetic resources. Access to plant genetic resources is fundamental to the development of more resilient and nutritious crops. The efficient and effective conservation of plant genetic resources is therefore key to ensuring global food security. There are more than 1750 genebanks around the world, storing various types of plant germplasm including tissue cultures, seeds, embryos and pollen. The chapter describes some of the recent applications of science and technology to improve the management of genebank collections of orthodox seeds, not least through the introduction of automation. In addition, the chapter looks at how routine cryopreservation procedures are now possible for many species, and how storage procedures for recalcitrant-seeded and vegetatively propagated species continue to evolve given the challenges they present in terms of long-term ex situ germplasm conservation.

Part 2 concludes with an analysis of the role of the Svalbard Global Seed Vault in preserving crop genetic diversity. Chapter 9 provides an overview of this facility in Svalbard and describes its operations as well as its functions and status. Genetic material in individual genebanks is potentially vulnerable to being lost (e.g. through conflict or a natural disaster). One important and simple security measure is to ensure that samples of these valuable genetic materials are conserved in more than one place. In this context, the Svalbard Global Seed Vault offers a free of charge service to store duplicate samples of seeds that are conserved in genebanks world-wide.

Part 3 Enhancing conservation and use of plant genetic diversity

The final part of the book begins with a discussion on community-based conservation of crop genetic resources. Chapter 10 explores the current state of research, knowledge and practice of community-based conservation in the context of continued farmer-driven processes and the emergence of diverse external interventions. Autonomous community-based conservation is largely powered by farmer demand for crop diversity. Cultural, provisioning and regulating ecosystem services play an essential role. It is argued that an enhanced understanding of the drivers and rationales influencing farmers decision-making continues to be essential under the current scenario of accelerated global change. A large and diverse portfolio of exogenous interventions have emerged since on-farm conservation has become a development issue. A variety of different interventions designed to support on-farm conservation for are reviewed. The chapter also highlights the need for an effective monitoring framework for community-based management of crop genetic resources. Such a systems could enhance the measurement, metrics and intelligence underlying the on-farm conservation status of crops and landraces.

Chapter 11 reviews participatory plant breeding programmes to optimize use of crop genetic resources. The chapter summarises a sample of variety evaluation, experimental design, and breeding method innovations that have served as solid approaches for participatory plant breeding (PPB) efforts. With success in PPB comes success in conservation at a local level of useful alleles and allele assemblages in the form of on-farm crop genetic resources. PPB programs of this sort have the potential to add value to local or traditional varieties that might otherwise be abandoned, thus promoting their *in-situ* conservation. The chapter briefly touches on methodologies to assess farmers' variety preferences. This is followed by sections that highlight some experimental designs for on-farm variety evaluation and farmer-participatory breeding methods for combining in-situ conservation with genetic improvement. Finally, some of the challenges that may limit genetic gain from PPB programs are noted – problems that increase the risk of wholesale replacement of on-farm genetic diversity rather than conservation through improvement.

Moving on to Chapter 12, this chapter examines seed systems and diversity. Farmers use various seed systems to obtain seeds for their next crop. The diversity of seeds determines, together with other aspects of the farming system, the biodiversity in farmed areas. Conservation strategies for crop genetic resources distinguish ex situ, on-farm and in situ components. The on-farm management of such resources is highly influenced by the seed systems that farmers use. Next to primary and secondary centres of diversity, this chapter introduces a tertiary source of diversity, based on the creation of new diversity through modern breeding. The impact of different seed systems on the management of crop genetic diversity is also analysed.

Chapter 13 concludes the book by providing an overview of DNA-based screening of Brassica germplasm for sustainable and enhanced crop production. The Brassica genus contains many agriculturally important oilseed and vegetable crops. Brassica germplasm, including natural accessions and breeding populations, are maintained globally for sustainable management and enhancement of Brassica crop production which is critical to meet the demands of population growth and challenges of environmental stresses due to global climate change. DNA based markers, such as SNPs, are commonly used to screen large numbers of Brassica germplasm for conservation, genetic mapping and association studies. The chapter focuses on the application of SNP genotyping technologies for conservation of Brassica germplasm, uncovering the genetic basis of various biotic and abiotic stresses and screening for yield related traits and oil quality through marker-trait association studies.

Chapter 1

Plant genetic resources for food and agriculture for sustainable development[1]

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1 Introduction

In 2019, about 2 billion people across the world lacked regular access to safe, nutritious and sufficient food (FAO, IFAD, UNICEF, WFP and WHO, 2020). This dire statistic, which mirrored the earlier estimation of about 2.5 billion people who suffer from various forms of nutrient deficiencies and obesity globally (FAO, IFAD, UNICEF, WFP and WHO, 2018, 2019), underscored a progressively

1 The views expressed in this publication are those of the authors and do not necessarily reflect the views or policies of the Food and Agriculture Organization of the United Nations. This chapter is © Food and Agriculture Organization of the United Nations.

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worsening state of global food insecurity and malnutrition. With increasing global population expected to reach 9.7 billion by 2050 (Anon, 2020), whereby the steepest increases are in food insecure countries of the developing South, it is estimated that 50% more food, over the 2013 baseline, needs to be produced by 2050 in order to meet the ever-increasing demands (FAO, 2017a). Yet, with climate change imperiling crop production systems, there are scarcely any redundant arable lands and water resources to be further deployed for food production. It is against this challenging backdrop that the world, through the Sustainable Development Goals (SDGs), committed to a world free of hunger and malnutrition in the next 10 years (UN General Assembly, 2015; FAO, 2017a).

The prohibitive economic and environmental costs and dangers to human health make the use of additional external inputs (such as agrochemicals) non-viable options for the significantly increased food production needed for a hunger-free world. Therefore, it is certain that a business-as-usual mind-set is not an option. In the absence of additional agricultural natural resources base for increased deployment and the impracticality of unbridled increases in the use of external inputs, the inherent potentials of our crops must be tapped to enhance their productivities, that is, producing more yields with fewer inputs. It is in this vein that the Food and Agriculture Organization of the United Nations (FAO) called for a new paradigm of sustainable crop production intensification (SCPI) in which a genetically diverse portfolio of improved crop varieties that are best suited to agroecosystem and farming practices and more resilient to climate change should be promoted (FAO, 2011). Similarly, the further development of agriculture, and the world's continued food security, will depend on farmers and breeders continuing to have access to and use diverse plant genetic resources necessary to face new environmental and social challenges.

Our optimism regarding the prospects of this paradigm derives from the knowledge that the first wave of crop domestication over 10 000 years ago resulted in the current agricultural systems on which the global food security and nutrition depend (McCouch, 2004; Waines and Ehdaie, 2007). The repertoire of wild ancestors or related species of crops – known as crop wild relatives (CWR); non-related species which are donors of heritable traits used in plant breeding; farmers' varieties or landraces and modern crop varieties is referred to as plant genetic resources for food and agriculture (PGRFA) (FAO, 2009). In essence, PGRFA are plants used, or with potentials to be used, for food and other agricultural purposes and therefore encompass the diversity of the plant kingdom that underpin global food security and nutrition. The values of crops, which are cultivated and harvested for food or other uses, and wild and undomesticated plants that are similarly exploited as food, are obvious. However, perhaps more importantly, PGRFA also serve as a huge reservoir of heritable traits that enable crops to adapt to physical and biological stresses, for example, drought, heat, cold, pests and diseases – the direct consequences of climate change, and to enhance the nutritional attributes of crops (Mba et al., 2012).

The commitment of the international community to make PGRFA freely available, especially for research and development, through various normative processes and instruments is reviewed in the subsequent sections of this chapter. The actions that may be taken – through the conservation of PGRFA in situ and ex situ and the maintenance of on-farm diversity; their use in breeding progressively superior crop varieties; and delivery to farmers via effective seed systems to ensure that humanity benefits from these irreplaceable resources in ways that safeguard them for current and future generations are also highlighted. This chapter, in providing examples of these aspects of the conservation and sustainable use of PGRFA, also highlights the scientific and technological advances that make these possible. Finally, perspectives are shared on the imperative of the creation of the enabling environment and the fostering of winning partnerships for the sustainable management of PGRFA, especially with regard to unlocking their potentials through research and development.

2 Plant genetic resources for food and agriculture (PGRFA): a common concern for all countries

Today, cassava – *Manihot esculenta* Crantz – is a far more important food security crop in sub-Saharan Africa into which it was first introduced by Portuguese sailors in the 16th century than in the countries, Brazil and Bolivia, which adjoin the Amazon basin where it was originally domesticated several tens of millennia ago. In like manner, oil palm – *Elaeis guineensis* Jacq. – with the evidence of its use as food dating as far back as five millennia in West Africa, its primary centre of genetic diversity, is a far more major cash crop in Asian countries, Malaysia and Indonesia, into which it was introduced a few decades ago.

Other crops such as maize, potatoes, wheat, barley and rice are now so ubiquitous around the globe that it is not obvious to the average consumer that they were introduced into most of the places where they have become seemingly irreplaceable staples. Also, the pioneering collecting expeditions of the likes of N.I. Vavilov and Jack Harlan early in the 20th century are well chronicled along with the concerns they raised about the decline in the diversity of crops as evidenced by the increasingly diminishing cultivation of traditional crop varieties or landraces and their undomesticated relatives, that is, CWR on-farm and in nature, respectively (Vavilov, 1931; Harlan, 1957).

These probably explain why the international community has consistently, while demonstrating the critical importance of PGRFA to global food security and nutrition, also underscored the interdependence among nations as means to derive the most benefit from these resources. For instance, the FAO called for immediate action for the collection and conservation of landraces and CWR at the 10th session of its Conference in 1959. Following this, two major technical meetings in 1961 and 1967 took place. These were the Technical meeting on Plant Exploration and Introduction which was convened in 1961 to streamline germplasm conservation and distribution and established exploration centres in regions of greatest diversity (Scarascia-Mugnozza and Perrino, 2002). The 1967 International Technical Conference organized jointly by the FAO and the International Biological Programme (IBP) was a landmark conference that aimed to articulate a global strategy for the conservation of PGRFA. A Panel of Experts was constituted to develop the guidelines for the establishment of a global network for ex situ conservation and the associated plan of action (Frankel and Hawkes, 1975). The proposal of the Panel was presented at the 1973 FAO/IBP Technical Conference and subsequently was considered by the Technical Advisory Council of the CGIAR. This in turn led to the creation of a coordinating centre, the International Board on Plant Genetic Resources (IBPGR) in the FAO (which later became the CGIAR centre, the International Plant Genetic Resources Institute, later renamed Bioversity International and now the Alliance of Bioversity International and CIAT). The IBPGR was operated under the aegis of the FAO to promote and assist in the worldwide efforts to collect and conserve plant germplasm needed for future research and crop production (Scarascia-Mugnozza and Perrino, 2002).

Ever since, the international community, especially through the FAO's leadership, has been most active in emphasizing the interdependence of nations in both the responsibility of safeguarding PGRFA and the mutual benefits of using them. FAO's intergovernmental work on the conservation and use of PGRFA has been carried out through its Commission on Genetic Resources for Food and Agriculture (Commission) established in 1983 (FAO, 2010). Starting out as the Commission on Plant Genetic Resources and in 1995 taking on the responsibility for other components of agricultural biodiversity, it is an FAO forum for governments to discuss and negotiate matters relevant to genetic resources for food and agriculture. It is the only intergovernmental body that specifically deals with all components of biological diversity for food and agriculture. In this regard, it reviews and advises the FAO on policy matters, programmes and activities. It was in this vein that the Commission facilitated a Global System on Plant Genetic Resources for Food and Agriculture (Global System) which is a set of policy instruments and mechanisms to promote the safeguarding of PGRFA, their availability and sustainable use (FAO, 2010; Frison et al., 2011). The elements of the Global System and related international agreements are described in the following sections.

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3 International agreements supporting the global system on PGRFA

The principal international agreements supporting the Global System on PGRFA are:

- International Undertaking on Plant Genetic Resources for Food and Agriculture;
- The Convention on Biological Diversity (CBD); and
- The International Treaty on Plant Genetic Resources for Food and Agriculture.

These are discussed in the following sections.

3.1 International undertaking on plant genetic resources for food and agriculture

Adopted by the FAO's Conference in 1983, the objective of this undertaking was 'to ensure that plant genetic resources of economic and/or social interest, particularly for agriculture, will be explored, preserved, evaluated and made available for plant breeding and scientific purposes. This undertaking is based on the universally accepted principle that plant genetic resources are a heritage of mankind and consequently should be available without restriction' (FAO, 1983). This set the tone for the ongoing recognition and treatment of PGRFA as a global commonwealth.

3.2 The convention on biological diversity (CBD)

The CBD is the international agreement for 'the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources' (United Nations, 1993). Biodiversity encompasses PGRFA. In fact, the Strategic Plan for Biodiversity 2011–2020, including the Aichi Biodiversity targets, of the CBD is aimed at the promotion and the conservation and use, *inter alia*, of PGRFA. Aichi Target 13 specifically addresses the maintenance of the genetic diversity of cultivated plants, that is, crops, and their wild relatives. Also, Aichi Targets 7 and 13 address PGRFA explicitly. The Tenth Conference of Parties (or COP 10) of the CBD also endorsed the Global Strategy on Plant Conservation (GSPC) that addresses the challenges posed by threats to plant diversity. Target 9 of the GSPC aims at conserving 70% of genetic diversity of crops including their wild relatives. The post-2020 Biodiversity Framework, presently under negotiation, continues to highlight the contribution of genetic diversity to Nature's contribution to people and new targets for maintaining and

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